Intelligent Sensor Systems for Integrated System Health Management in Exploration Applications

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OUTLINE

- INTRODUCTION
- SENSORS AND ISHM
- SENSOR DEVELOPMENT DIRECTION
- SENSOR EXAMPLES
  - SMART SENSORS
  - “LICK AND STICK”
  - SPRAY ON SENSORS
  - MULTIFUNCTIONAL PHYSICAL SENSOR
  - ORTHOGONAL SENSOR SYSTEMS
  - SUPPORTING TECHNOLOGIES
- GROUND TESTING
- TRANSITION TO FLIGHT
- SYSTEM LEVEL SUGGESTIONS

ISHM AND SENSOR MOTIVATION FOR EXPLORATION

- FUTURE EXPLORATION MISSIONS WILL REQUIRE SIGNIFICANTLY IMPROVED INTEGRATED SYSTEM HEALTH MANAGEMENT (ISHM) THROUGHOUT THE VEHICLE
  - LIMITED GROUND SUPPORT
  - CONSTRAINED IN TIME, RESOURCES, AND CAPABILITIES FROM PERFORMING EXTENSIVE SYSTEM MAINTENANCE, REPAIR, OR REPLACEMENT.
  - NEAR-EARTH MISSIONS REQUIRE IMPROVED SYSTEM SAFETY, RELIABILITY, AND EFFICIENCY.
  - IDENTIFY PROBLEMS BEFORE THEY CAUSE HARM
- VEHICLE SYSTEMS THAT REQUIRE INTENSE HUMAN INTERVENTION OR MONITORING ARE IMPEDIMENTS TO REALIZATION OF THE EXPLORATION VISION.
- INCLUSION OF AUTOMATED VEHICLE INTELLIGENCE INTO THE SYSTEM DESIGN AND OPERATION IS NECESSARY
- ENABLE INTERNAL SYSTEMS TO MONITOR COMPONENT CONDITIONS, ANALYZE THE INCOMING DATA, AND MODIFY OPERATING PARAMETERS TO OPTIMIZE SYSTEM OPERATIONS TO ACHIEVE IMPROVED PERFORMANCE AND RELIABILITY.
- IF PROBLEMS DO OCCUR, SOME AUTONOMOUS PROGNOSIS/DIAGNOSIS, FAULT ISOLATION, AND REMEDIATION IS NECESSARY I.E. THE VEHICLE WILL NEED INTEGRATED INTELLIGENCE AND ADVANCED ISHM SYSTEMS.

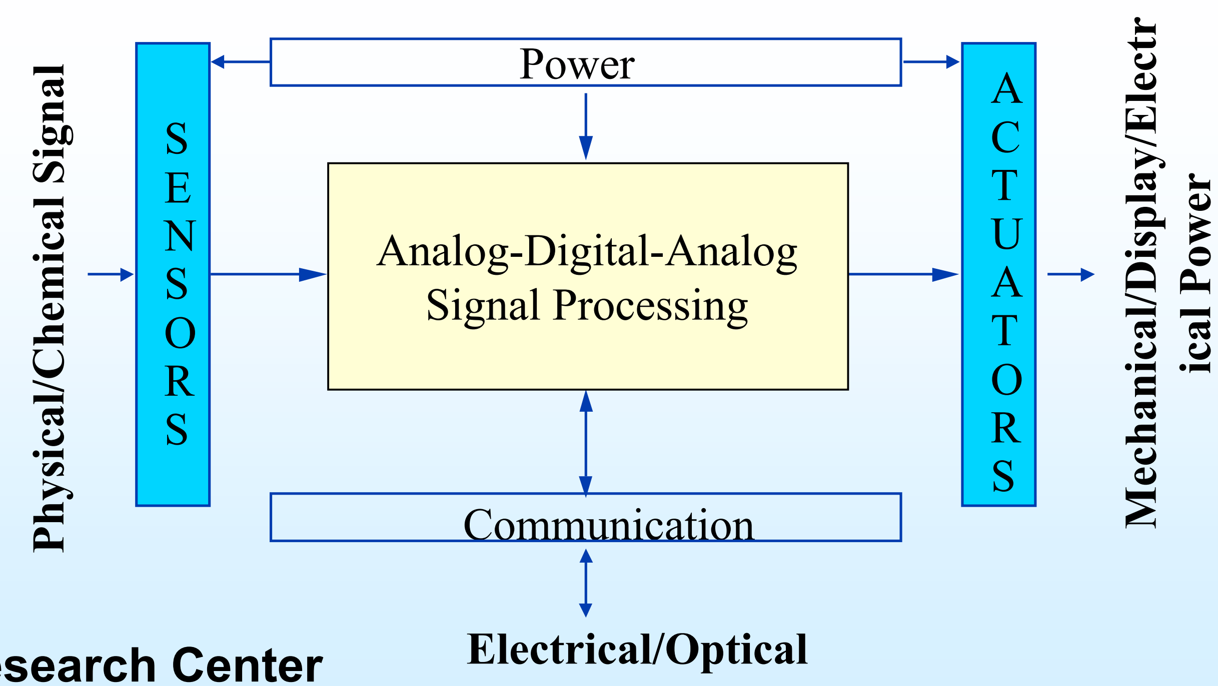
ISHM SENSOR SYSTEMS

- HIGH_QUALITY DATA PROVIDED BY SENSOR SYSTEMS IS A FOUNDATION OF ISHM
- PRESENT SENSOR TECHNOLOGY DOES NOT MEET NASA EXPLORATION NEEDS. NASA NEEDS IN SENSORS ARE SPECIALIZED AND REVOLVE AROUND ITS UNIQUE MISSION. OFF-THE-SHELF TECHNOLOGY IS OFTEN NOT APPLICABLE:
  - ➢ DESIGNED FOR MARKETS WHERE SIZE, POWER, AND ALL-IN-ONE MULTIFUNCTIONALITY ARE NOT THE PRIMARY ISSUES.
  - ➢ SIZE, WEIGHT, AND POWER CONSUMPTION WOULD SIGNIFICANTLY AFFECT THE MISSION, POTENTIALLY RENDERING THE MISSION UNTENABLE.
  - ➢ STANDARDLY OFF-THE-SHELF SYSTEMS OFTEN DO NOT MEET NASA SPECIFICATIONS I.E. RADIATION HARDENED, YEARS OF OPERATION WITHOUT POSSIBLE HUMAN INTERVENTION, LIMITED SPARE PARTS, ETC.
  - ➢ SENSORS NEED TO BE TAILORED FOR THE APPLICATION
- IF ISHM IS GOING TO BE EFFECTIVE, THEN IT SHOULD BE APPLIED WHERE IT IS NEEDED, NOT JUST WHERE IT IS CONVENIENT.
  - ➢ FOR EXAMPLE, LIMITED ON-BOARD HARSH ENVIRONMENTS SENSORS LEAVING SIGNIFICANT AREAS OF THE PROPULSION SYSTEM UNMONITORED.
- WHILE NASA MIGHT LEVERAGE SENSOR TECHNOLOGY BEING DEVELOPED ELSEWHERE, NASA UNIQUE PROBLEMS REQUIRE SPECIALIZED SOLUTIONS.

ISHM SENSOR SYSTEM DEVELOPMENT

- DO NOT ASSUME IT WILL JUST BE THERE WHEN NEEDED
- SENSORS AND ISHM INCLUSION OFTEN PROBLMATIC IN VEHICLE SYSTEMS
  - LEGACY SYSTEMS
  - CUSTOMER ACCEPTANCE
  - LONG-TERM VS SHORT TERM CONSIDERATIONS
- THIS PRESENTATION CONCENTRATES ON STEPS TO ENABLE INTELLIGENT SENSOR SYSTEMS FOR INTEGRATED SYSTEM HEALTH MANAGEMENT
- RANGE OF SYSTEM ASPECTS NEED TO BE CONSIDERED
- DISCUSSES DIRECTIONS IN SENSOR TECHNOLOGY

Microsystem Block Diagram



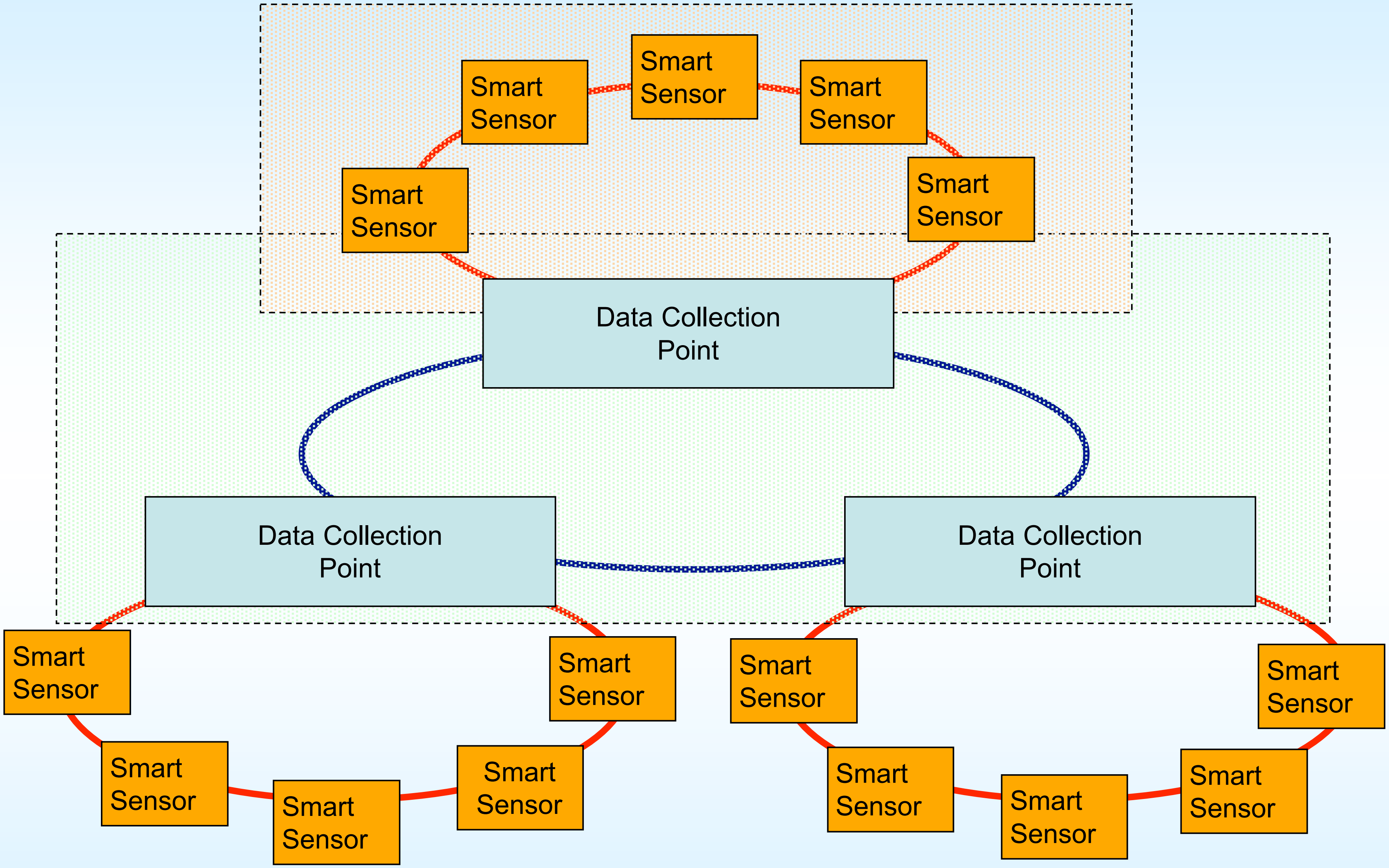
POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS

- "LICK AND STICK" TECHNOLOGY (EASE OF APPLICATION)
  - Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.
- RELIABILITY:
  - Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations e.g. decreasing sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur is it can be trusted.
- REDUNDANCY AND CROSS-CORRELATION:
  - If the systems are easy to install, reliable, and not increase weight/complexity, the application of a large number of them is not problematic. This allow redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.
- ORTHOGONALITY:
  - Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to "see, feel, smell, hear" as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.

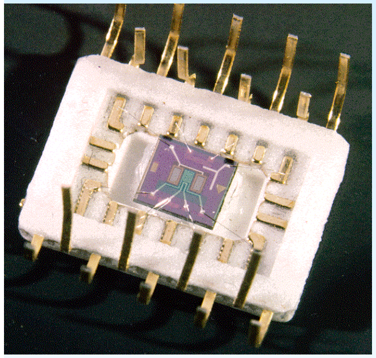
ISHM ARCHITECTURE USING SMART SENSORS

- BASED ON INTELLIGENCE RESIDING WITHIN EACH SMART SENSOR CONTRIBUTING TO THE INTELLIGENCE OF THE COMPLETE SYSTEM.
- EACH SMART SENSOR WILL HAVE EMBEDDED INTELLIGENCE THAT WILL ALLOW IT TO CHECK ITS OWN HEALTH AND TO VALIDATE THE DATA PROVIDED TO A DATA COLLECTION POINT. SMART SENSORS ALLOW AN ISHM ARCHITECTURE APPROACH WHICH
  - RELIES ON ACQUIRING INFORMATION FROM SMART SENSORS AND ACTUATORS,
  - PROCESSING THIS INFORMATION,
  - COMPARING/AUGMENTING THE INFORMATION PROVIDED BY THE SENSORS' EMBEDDED KNOWLEDGE TO ITS OWN KNOWLEDGE INFORMATION SYSTEM,
  - ESTABLISHING THE HEALTH OF THE SYSTEM
- PROCESS AND DIAGNOSTIC AGENTS, AND COMMUNICATION PROTOCOLS ALLOWS:
  - ACQUIRE RAW DATA AND CONVERT THE DATA TO ENGINEERING UNITS
  - PROCESS THIS ENGINEERING DATA, AND
  - EXTRACT HEALTH IN-FORMATION TO BE TRANSMITTED AMONG THE OTHER SENSORS AND FROM SENSOR TO NEXT HIGHER ASSEMBLY (DATA COLLECTION POINTS).

ISHM ARCHITECTURE USING SMART SENSORS.



HYDROGEN LEAK SENSOR TECHNOLOGY

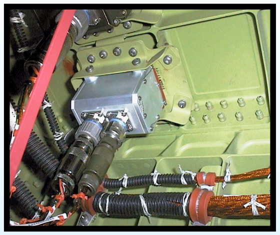


- MICROFABRICATED USING MEMS-BASED TECHNOLOGY FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- HIGHLY SENSITIVE IN INERT OR OXYGEN-BEARING ENVIRONMENTS, WIDE CONCENTRATION RANGE DETECTION

1995 R&D 100 AWARD WINNER

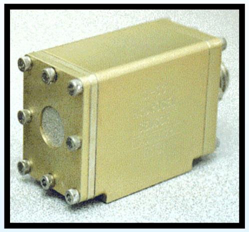
NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD

Shuttle



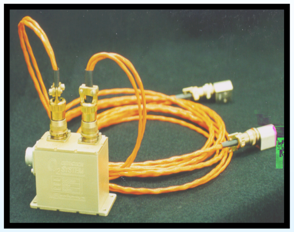
Aft Compartment Hydrogen Monitoring

X33



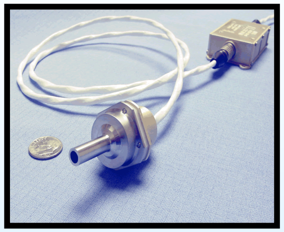
Hydrogen Safety Monitoring

X43



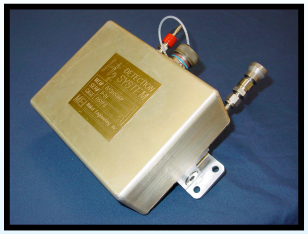
Hydrogen Safety Monitoring

Helios



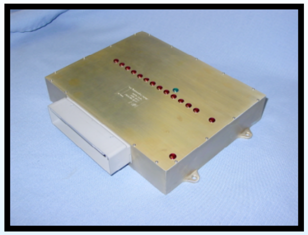
Fuel Cell Safety and Process Monitoring

ISS



Life Support Process and Safety Monitoring

Model U



Vehicle Safety Monitoring

MEI Makel Engineering Inc.

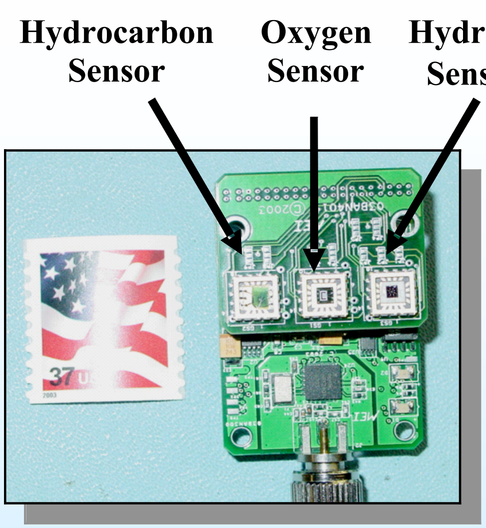
CWRU

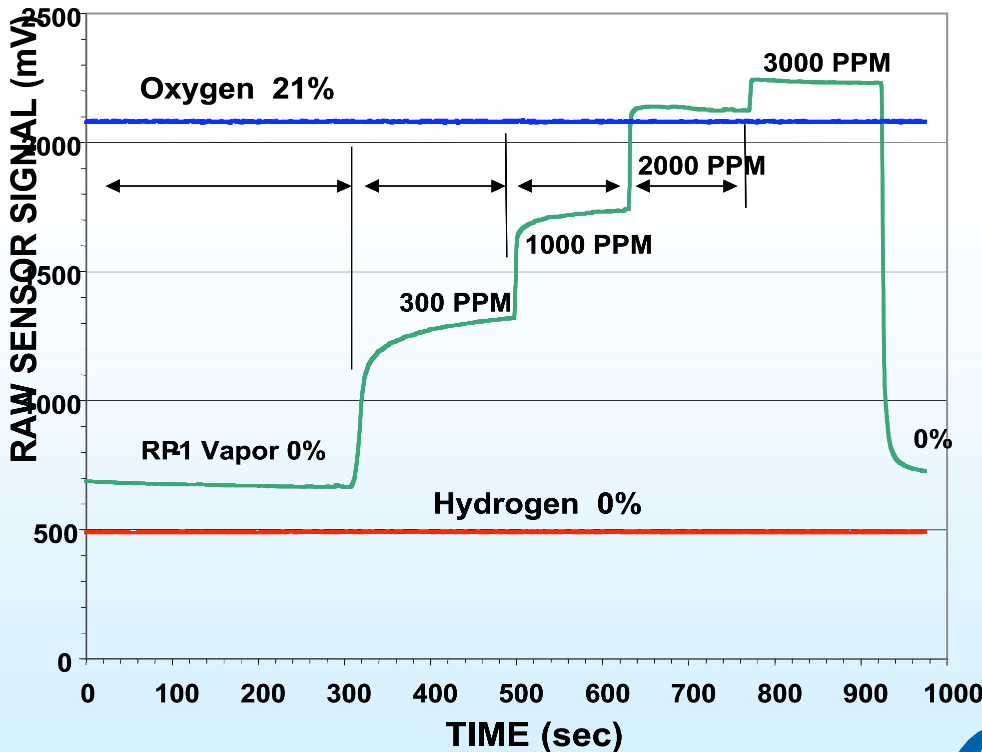
Glenn Research Center

Instrumentation and Controls Division

“LICK AND STICK” LEAK SENSOR SYSTEM DEMONSTRATION

- FUEL/OXYGEN LEAK DETECTION WITH POWER, SIGNAL CONDITIONING, TELEMETRY ALL IN THE SURFACE AREA OF A POSTAGE STAMP
- THREE SENSORS
  - NEAR ROOM TEMPERATURE Si SENSOR WITH HIGH AND LOW H2 MEASUREMENTS
  - ELECTROCHEMICAL CELL FOR O2
  - WIDE TEMPERATURE RANGE SiC SENSOR: H2, HYDROCARBONS, HYDRAZINE
- GOAL: DETECT EXPLOSIVE CONCENTRATIONS FOR MULTIPLE VEHICLES, A WIDE RANGE OF FUELS WITH “LICK AND STICK” SYSTEMS

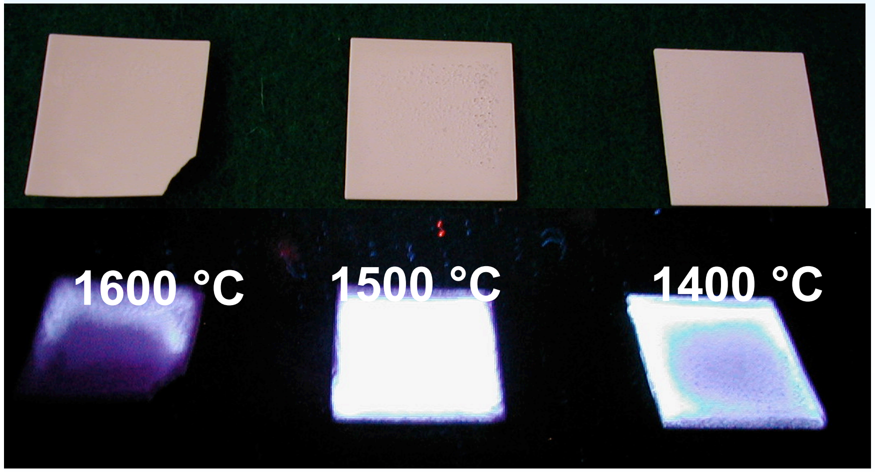




Temperature Sensitive Paint

- Binder/Phosphor combination has been demonstrated to work at 1500C;
- Phosphors alone operational to 1700C.
- Intensity decreases at ~1300C, but measurements are still possible at the higher temperatures.

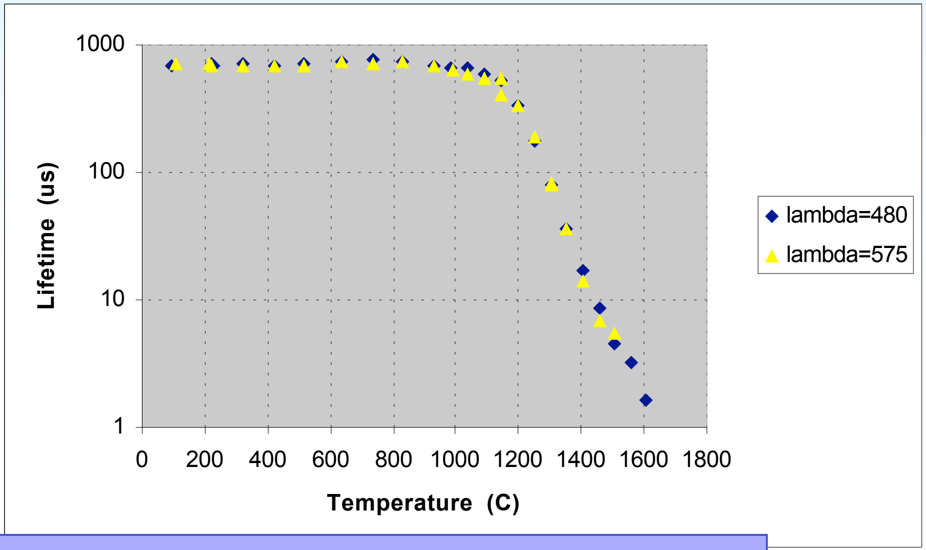
Visible Light



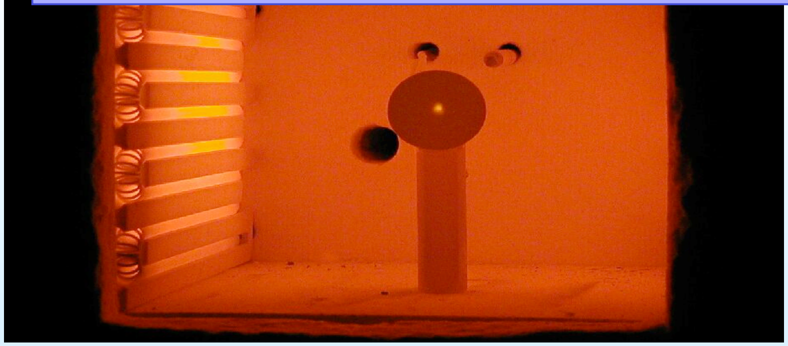
254 nm UV Light

Full-field calibration measurements @ 1000C made using gated digital camera

Emission at 610 nm,
excited by 355 nm at ~700 C



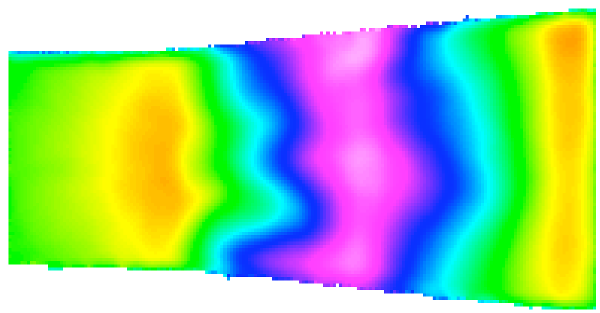
Lifetime decay vs Temperature shows measurable signal to 1500C



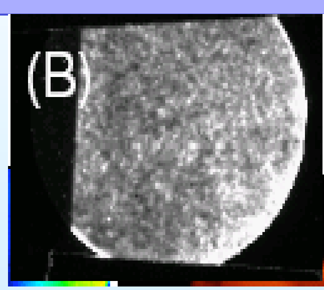
TEMPERATURE SENSITIVE PAINTS
SPRAY-ON SENSORS

- **Temperature sensitive paints yield quantitative, full surface information, greatly improving understanding of flow.**
- **Similar technology (pressure sensitive paint) used on ISTAR inlet in 1x1 foot supersonic wind tunnel.**

Typical low temperature surface results on a nozzle wall

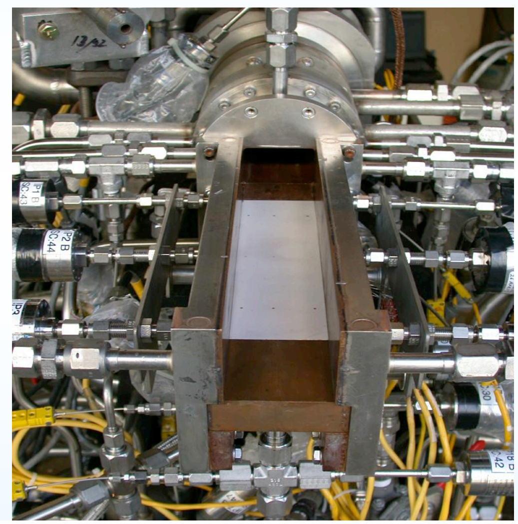


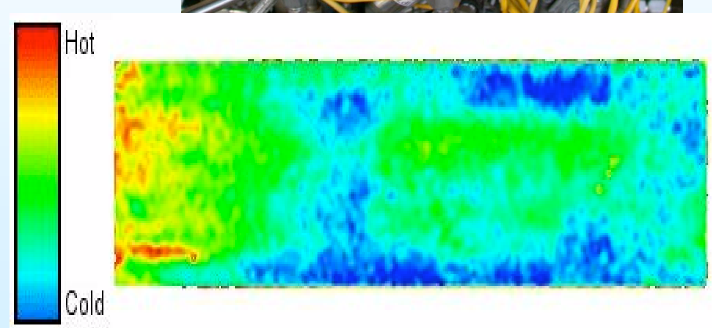
Heat transfer concept invented: Proof-of-concept results



YSZ-TBC

TSP Rocket Plume Test with water cooled panel

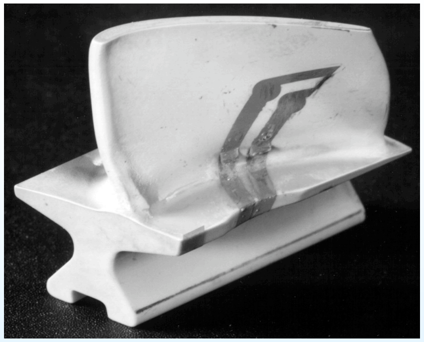




THIN FILM SENSOR TECHNOLOGY

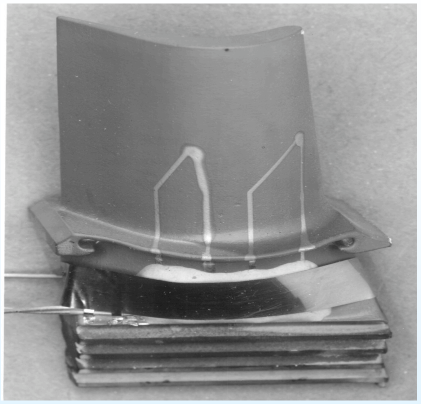
- VERY THIN, MINIMALLY INTRUSIVE SENSORS ABLE TO PROVIDE HIGH TEMPERATURE DATA WITHOUT DISTURBING AIR FLOW
- CAN BE FABRICATED DIRECTLY ON CERAMIC AND METAL ENGINE PARTS WITHOUT THE NEED TO CUT INTO THE PART.
- CAN BE APPLIED TO METAL BASED MATERIALS, CERAMIC MATERIALS, AND CERAMIC MATRIX COMPOSITES.
- MULTIFUNTIONAL, INFORMATION RICH SENSORS CURRENTLY UNDER DEVELOPMENT

1995 R&D 100 Award

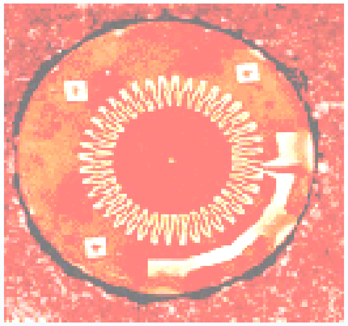


PdCr THIN FILM GAUGE APPLIED ON ALLIED-SIGNAL ENGINES CERAMIC TURBINE BLADE

THIN FILM THERMOCOUPLES ON CERMIC MATRIX COMPOSITE HOOP



THIN FILM THERMOCOUPLES ON SPACE SHUTTLE MAIN ENGINE TURBINE BLADES

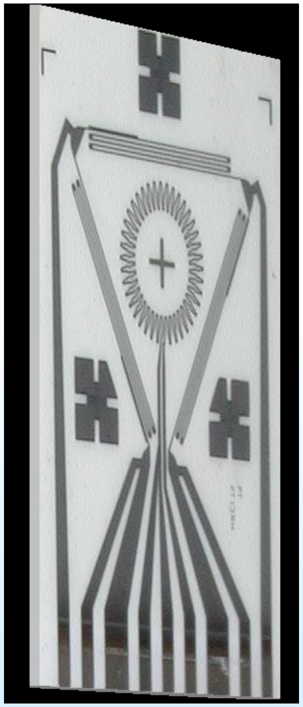


HEAT FLUX GAGE ON SILICON NITRIDE PLUG

Multi-Functional Sensor System

- MULTIFUNCTIONAL SENSOR PROTOTYPE WHICH COMBINES TEMPERATURE, STRAIN, HEAT, AND POSSIBLY FLOW RATE IN ONE SENSOR
- MULTIPARMETER MEASUREMENTS IN SENSOR OF MININIMAL SIZE
- MORE FULL-FIELD KNOWLEDGE OF ENVIRONMENT/CORRELATION OF DATA
- THIN FILM CAN BE DEPOSITED DIRECTLY ON SURFACE OR ON SUBSTRATE TO BE MOUNTED ON THE SURFACE

Multi-Functional Sensor

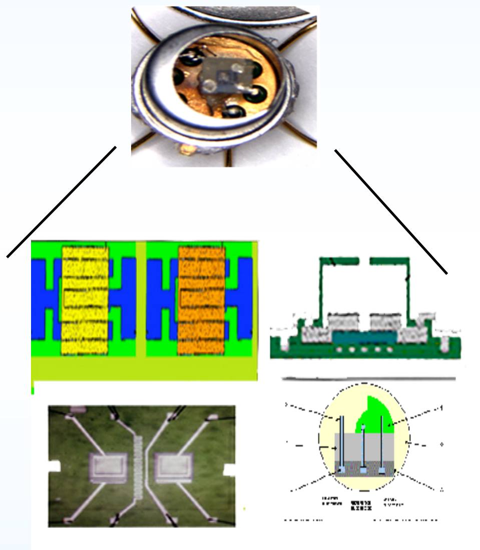


Micro-Fabricated Gas Sensors for Low False Alarms

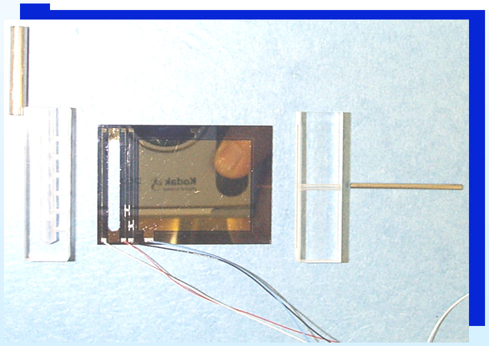
2005 R&D 100 AWARD WINNER

NASA 2005 TURNING GOALS INTO REALITY AA'S CHOICE AWARD

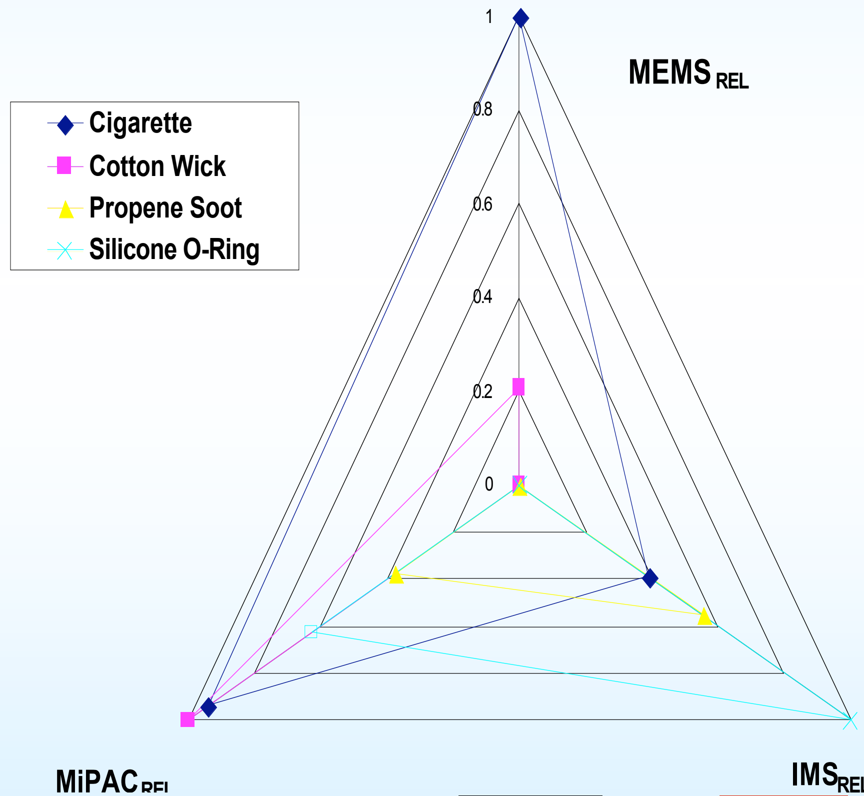
- DECREASE CARGO BAY FALSE ALARM RATE AS HIGH AS 200:1
- APPROACH: COMBINED MEMS-BASED CHEMICAL SPECIES AND PARTICULATE
- ORTHOGONAL DETECTION AND CROSS-CORRELATION SIGNIFICANTLY REDUCES FALSE ALARMS



MEMS-Based Chemical Species Detection



MEMS-Based Particulate Detector



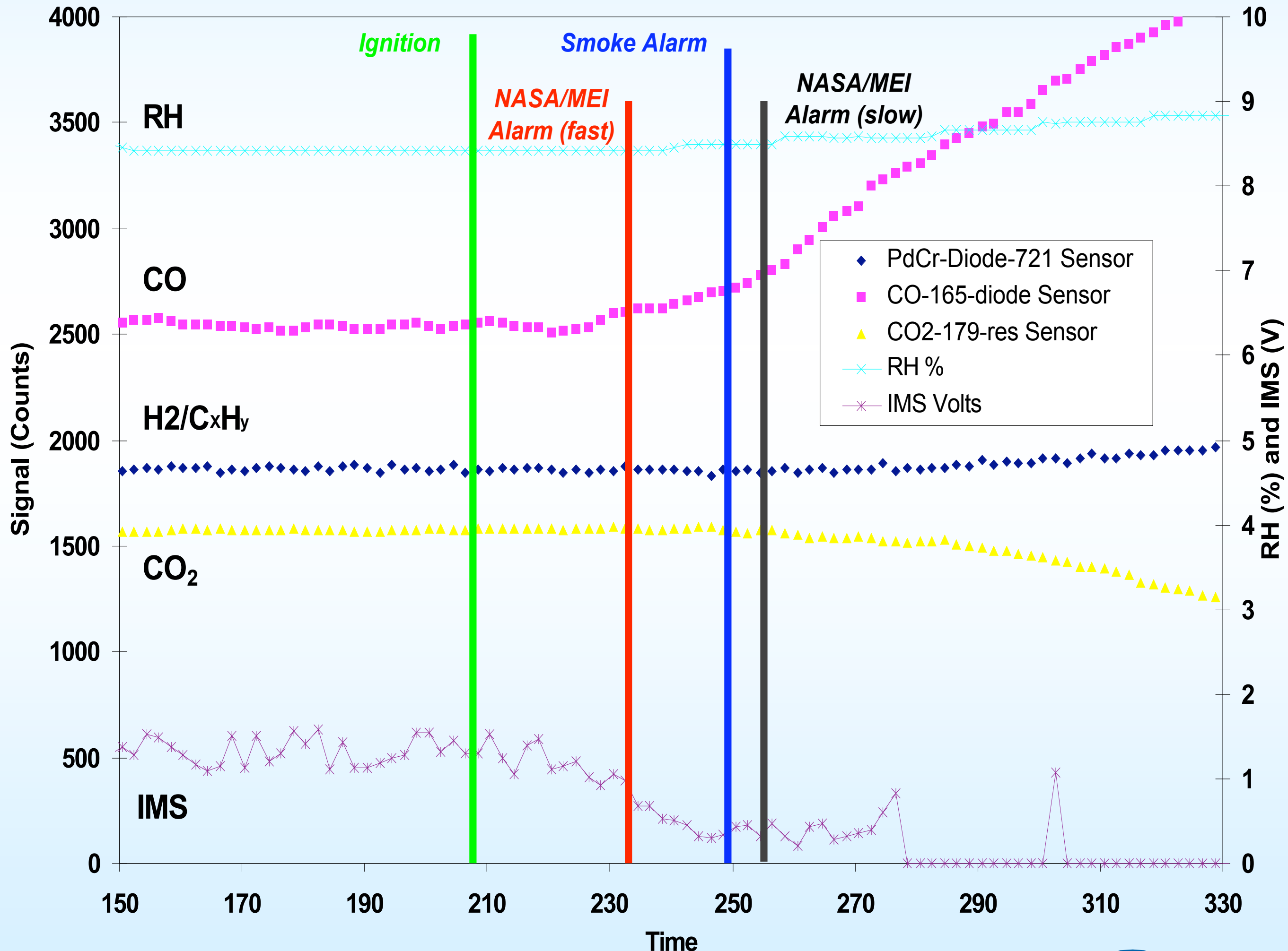
Glenn Research Center

Makel Engineering, Inc.

FAA Cargo Bay Fire Testing

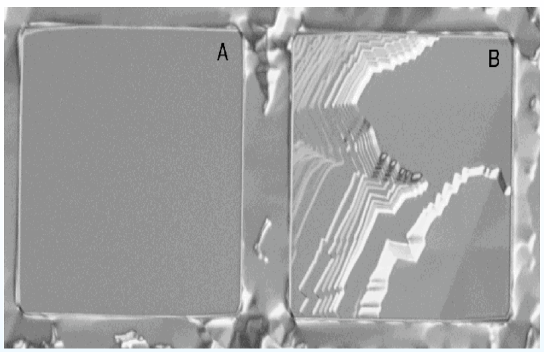
No False Alarms/Consistent Detection of Fires

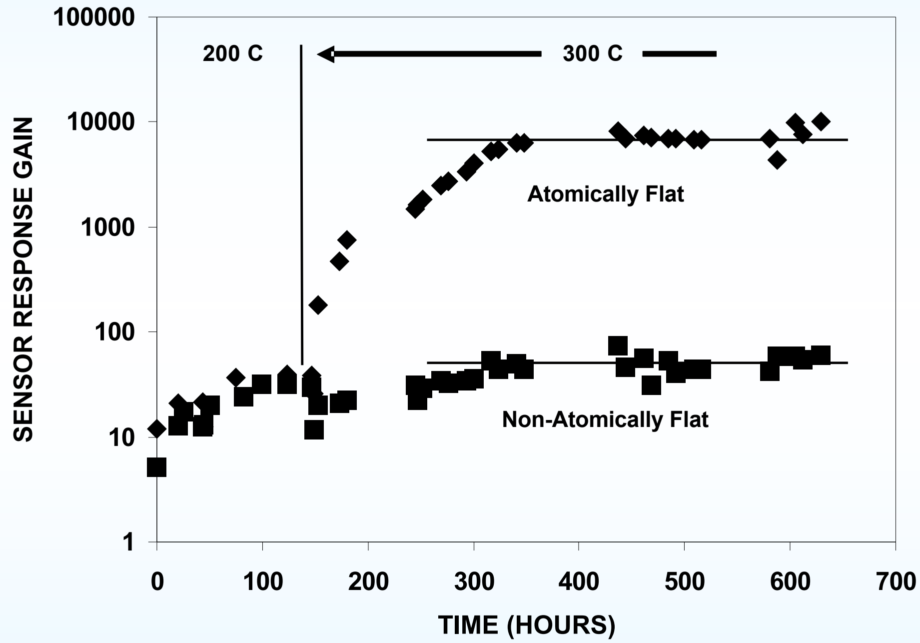
FAA Cargo Bay Fire Simulation Testing



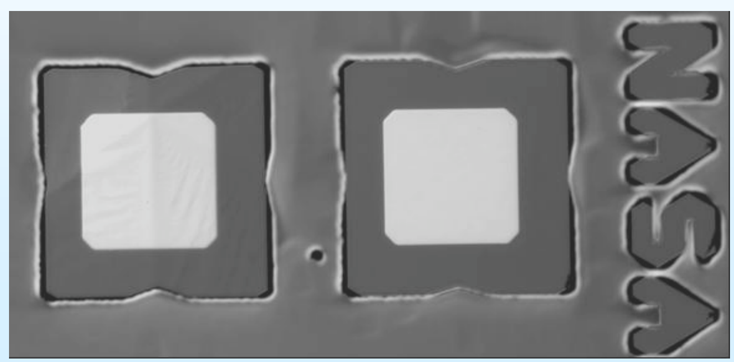
SUPPORTING TECHNOLOGIES:
HIGHLY LIMITED IN SOME APPLICATIONS

EXAMPLE: HIGH TEMPERATURE ELECTRONICS
(PROCESS INFORMATION AND COMMUNICATE)
ADVANCES IN SiC SEMICONDUCTOR EPILAYER GROWTH





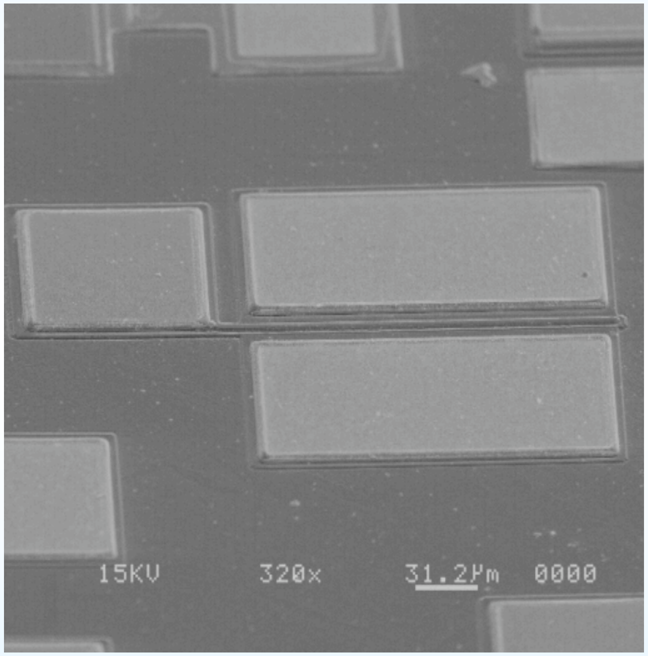
**PROCESSING RESULTS IN
"STEP-FREE"
EPILAYER SURFACE**

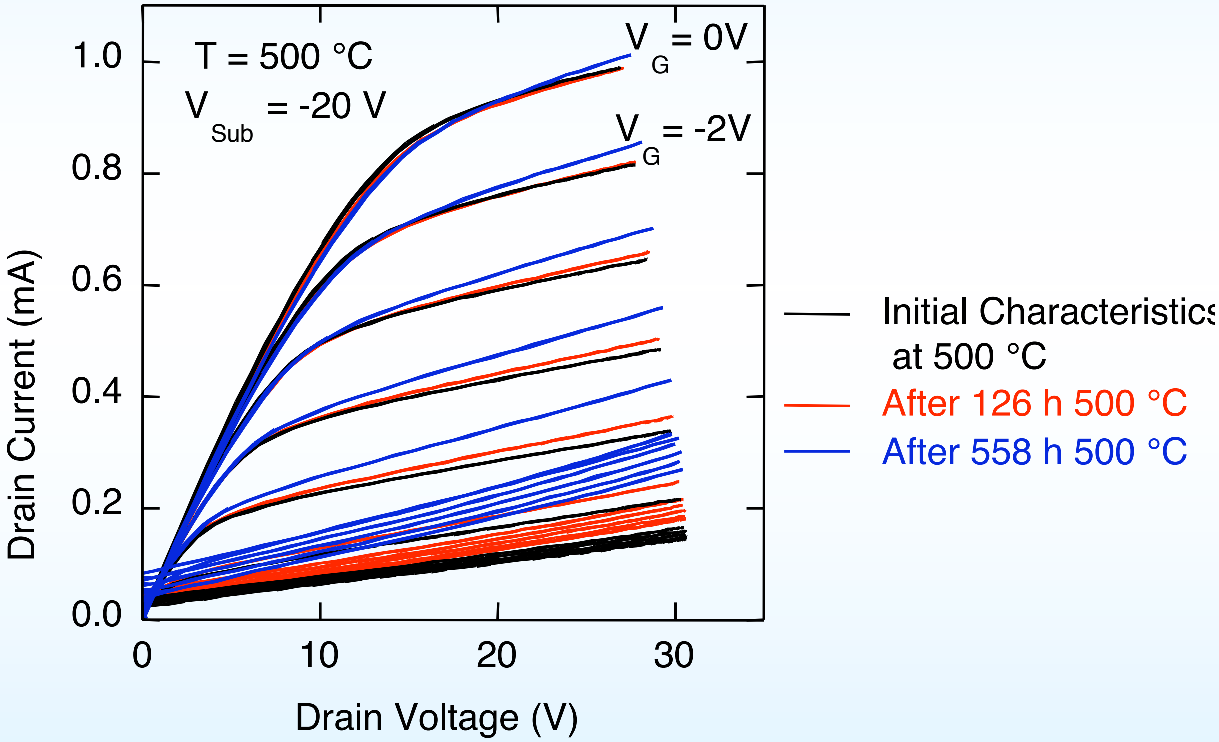


PROCESS INFORMATION AND COMMUNICATE

WORLD'S FIRST 500 HOUR 500 °C TRANSISTOR WITH VERY STABLE OPERATION

- 2000 hours of transistor operation achieved (some limited degradation)
- Device Operation Also Demonstrates Viability of Supporting Technologies
  - ➢ Packaging and ohmic contacts operated over 2000 hours at 500 °C without degradation.

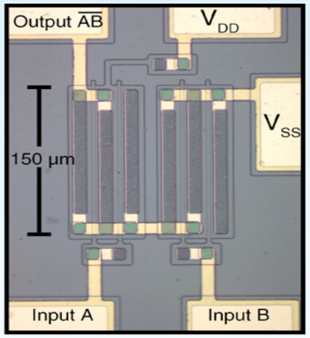




WORLD'S FIRST 500 C STABLE TRANSISTOR AND ITS PERFORMANCE OVER TIME

High Temperature Wireless Development

OBJECTIVES:
HIGH TEMPERATURE WIRELESS TELEMETRY, DISTRIBUTED ELECTRONICS OVER A BROAD OPERATING RANGE

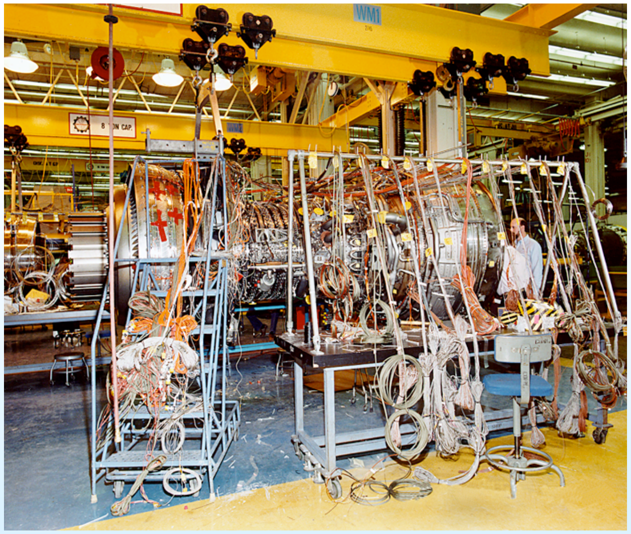


SiC JFET Multiplexor IC Chip

TECHNICAL CHALLENGES:
- DEVELOPMENT OF RELIABLE HIGH TEMPERATURE TELEMETRY ELECTRONICS, POWER SOURCES, REMOTE COMMUNICATION ELECTRONICS, AND PACKAGING

GOALS SUPPORTED:
- ENHANCE PERFORMANCE
- SIGNIFICANTLY REDUCE COST

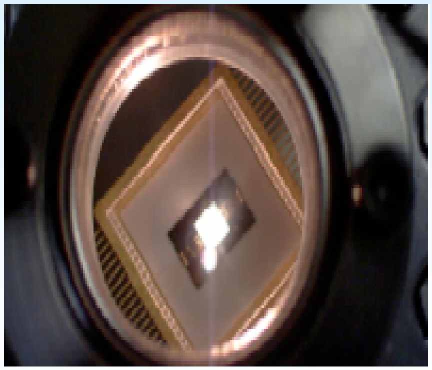
Gas Turbine Engine Development Requires Extensive Instrumentation



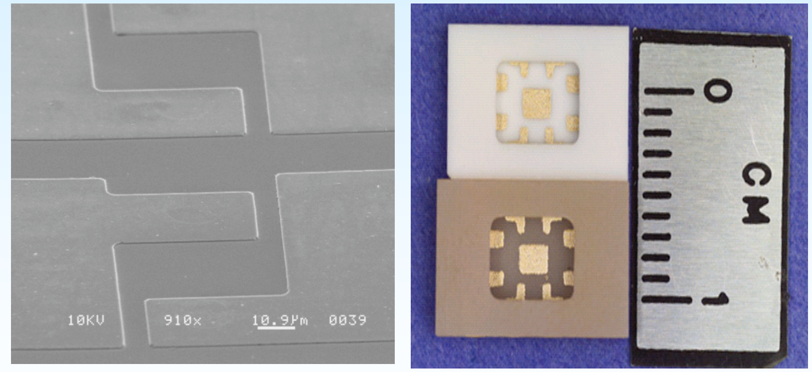
Wires from 1000 Sensors

SUPPORTING TECHNOLOGY DEVELOPMENT

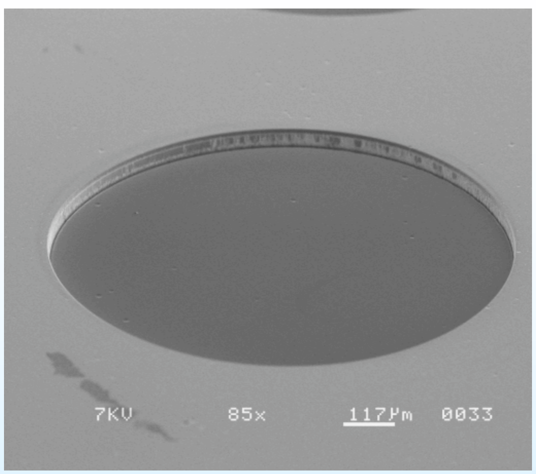
EXAMPLES OF OTHER ELEMENTS TO ENABLE INTELLIGENT SYSTEMS



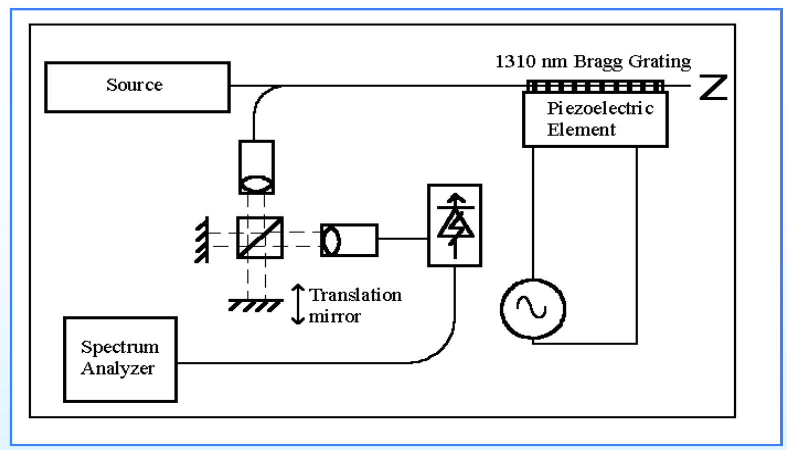
MEMS WHITE LIGHT SOURCE



HIGH TEMPERATURE CONTACT METALLIZATION AND PACKAGING



SiC MICROMACHINING

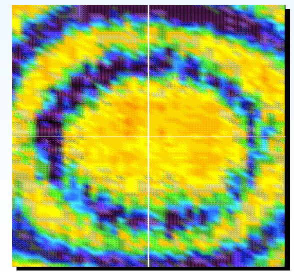


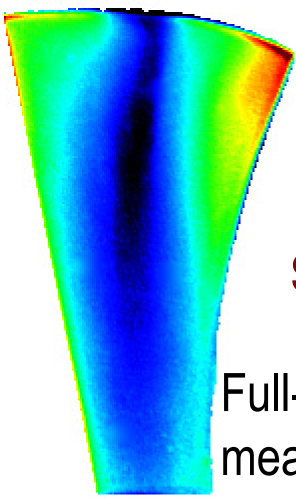
DYNAMIC SIGNAL PROCESSING FOR FIBER-OPTIC SPECTROMETERS

Advanced Optical Diagnostics for Ground Tests
Know the System Before Flight

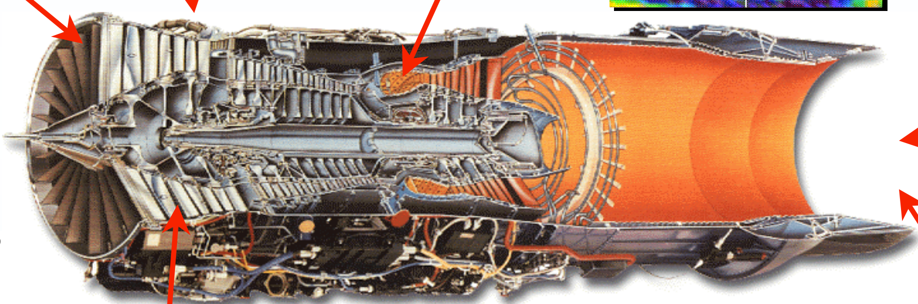
Electronic Holography
Neural Net processing for real-time damage detection

Planar Laser Induced Fluorescence
Fuel spray and species distributions

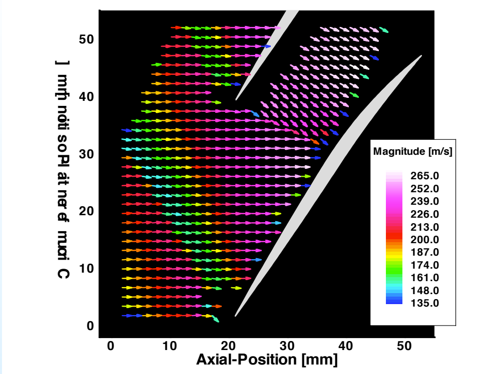




Pressure Sensitive Paint
Full-field measurements on rotating parts

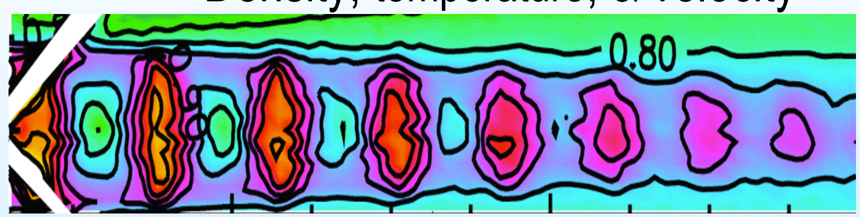


Focused Schlieren Imaging
nozzle mixing



Particle Imaging Velocimetry
Instantaneous and time-averaged planar velocity in confined spaces

Rayleigh Scattering
Density, temperature, & velocity



SENSOR DEVELOPMENT SUMMARY

- IT IS NECESSARY AND NOT JUST GOING TO SHOW UP WHEN NEEDED
- TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER/TAILOR SENSOR FOR NEEDS OF APPLICATION
- ONE INTELLIGENT SYSTEM APPROACH: SMART COMPONENTS (NODES) MADE POSSIBLE BY SMART SENSOR SYSTEMS
- SELF-AWARE COMPONENTS YIELD A SELF-AWARE SYSTEM
- HARSH ENVIRONMENT RESULTS IN SPECIAL CHALLENGES FOR COMPONENT TECHNOLOGIES
- SENSOR DIRECTIONS
  - EASE OF USE (LICK AND STICK)
  - RELIABILITY
  - REDUNDANCY AND CROSS-CORRELATION
  - ORTHOGONALITY
  - INTEGRATION/APPLICATION WITH SOFTWARE
  - SUPPORTING TECHNOLOGY/GROUND TEST
- EXAMPLE SYSTEMS:
  - SMART SENSORS; “LICK AND STICK”; MULITFUNCTIONAL; SPRAY-ON
- LONG-TERM VISION FOR AN INTELLIGENT SYSTEM IS A SYSTEM THAT IS SELF-MONITORING, SELF-CORRECTING AND REPAIRING, AND SELF-MODIFYING.
- NANOTECHNOLOGY MAY HAVE SIGNIFICANT IMPACT BUT IT MUST PROVE ITSELF

TRANSITION OF SENSOR SYSTEMS TO FLIGHT: SOME AREAS OF CONSIDERATION

- DEVELOPMENT OF A FULL LIFE-CYCLE PLAN FOR THE PRODUCT IS FUNDAMENTAL
  - TEAM COMPOSED OF THE PRODUCT DEVELOPER, THE END-USER, AND FLIGHT VEHICLE AND/OR GROUND SUPPORT . EXPERTS FROM SAFETY, RELIABILITY, LOGISTICS, SYSTEM INTEGRATION AND PROJECT MANAGEMENT.
- DETAILED SET OF REQUIREMENTS CRITICAL VERY EARLY IN THE PROCESS TO AVOID UNNECESSARY DELAYS AND/OR COSTLY REDESIGNS. INCLUDED ARE:
  - PERFORMANCE CONSIDERATIONS
    - EXAMPLES INCLUDE: LINEARITY, REPEATABILITY, HYSTERESIS, ACCURACY, MEASUREMENT RANGE, OUTPUT RANGE (FULL SCALE), OUTPUT TYPE (VOLTAGE, CURRENT, FREQUENCY, AND DIGITAL) AND POWER SUPPLY REQUIREMENTS.
  - PHYSICAL CONSIDERATIONS
    - EXAMPLES INCLUDE: SIZE, WEIGHT AND VOLUME MECHANICAL AND ELECTRICAL INTERFACE REQUIREMENTS
  - ENVIRONMENTAL CONSIDERATIONS
    - EXAMPLES INCLUDE: VIBRATION LEVELS AND DURATION, SHOCK LEVELS, ELECTROMAGNETIC INTERFERENCES (EMI), HUMIDITY, CORROSION, RADIATION, HEAT DISSIPATION, ETC.
  - SAFETY AND RELIABILITY CONSIDERATIONS
    - EXAMPLES INCLUDE INTRINSICALLY EXPLOSION OR TOXIC GAS EXPSOURE HAZARDS
- FAILURE MODES EVALUATION ANALYSIS SHALL BE CONDUCTED DURING THE QUALIFICATION OF THE PRODUCT.

SYSTEM LEVEL SUGGESTIONS

- ISHM INCLUDING SENSORS SYSTEMS BE INCLUDED INTO THE VEHICLE IN THE DESIGN PHASE.
- STUDY THE VEHICLE SYSTEM TO DETERMINE OPERATIONAL FUNCTION AND CRITICALITY OF VARIOUS SENSOR SYSTEMS AND HOW TO OPTIMIZE CROSS FUNCTIONALITIES.
- INSTRUMENT THE VEHICLE SYSTEM SHALL TO ALLOW MEASUREMENTS TO ENABLE DAMAGE/DEGRADATION PREDICTION AT A LEVEL TO ALLOW AUTONOMOUS OPERATION.
- DEMONSTRATE SENSOR RELIABILITY AND DURABILITY BEFORE INCLUSION OF SENSOR SYSTEM INTO VEHICLE.
- PERFORM SENSOR MEASUREMENTS TO OPTIMIZE MEASUREMENT OF MULTIPLE PARAMETERS SIMULTANEOUSLY TO IMPROVE FULL-FIELD SYSTEM INFORMATION AND MEASUREMENT RELIABILITY
- DEVELOP SENSOR SYSTEMS WHICH INCLUDE INTEGRATED INTELLIGENCE WHILE MINIMIZING SIZE, WEIGHT, AND POWER CONSUMPTION.
- AT MINIMUM, CRIT 1 SYSTEMS, I.E. THOSE WHOSE FUNCTION CAN AFFECT LOSS OF CREW AND/OR VEHICLE, SHOULD BE MONITORED NO MATTER THE EXTREME CONDITION INHERENT IN SUCH MONITORING

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